

## Development of a High Capacity Lithium-Ion Battery for a Navy Aircraft

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### Abstract

In response to the Navy's requirement for a lighter, higher capacity, secondary battery, Mine Safety Appliances Company (MSA) designed and built an experimental lithium-ion "drop-in" replacement battery for demonstration of its performance in the Pioneer aircraft. Lithium ion technology using a lithiated cobalt dioxide positive electrode, graphitized carbon negative electrode and liquid organic electrolyte has demonstrated a significant enhancement in performance over other rechargeable systems such as nickel-cadmium and nickel-metal hydride in comparable applications. Key features of the lithium ion system include higher gravimetric and volumetric energy densities, good charge retention (to maximize readiness), and zero memory effect. Such benefits outweigh a higher unit cost and the need for more stringent charge/discharge control. Design of the cells and battery, and preliminary battery test results are described.

### Introduction

The Navy uses a nickel-cadmium battery as an emergency backup power supply in the Pioneer aircraft. The battery has 24 nickel-cadmium cells wired in series to provide a nominal voltage of 28.8 volts and a capacity of 5 ampere-hours. The battery has a volume of 3 liters and weighs 4.3 kilograms. Taps are provided for two operating voltages rated at 28 volts and 15 volts, providing power for navigation and electronics, respectively. Bench acceptance test specifications require 34 minutes run time at 8 amperes to a 22 volt cutoff. Battery features include cell level diode protection, a plastic housing and a fully potted interior. A charger in

the aircraft charges the battery when the voltage falls below 32.4 volts and cuts off when the battery voltage reaches 35 volts.

### Cell Design and Selection

MSA's experimental battery uses 48 lithium-ion pouch cells. Each provides a nominal 3.6 volts and 1.5 ampere-hours when discharged between 4.1 volts and 3.0 volts. These cells are primarily used as test cells for other development work and are not optimized for energy density, specific energy or requirements of this application. However, they provide an expedient vehicle for this demonstration. Cells use  $\text{Li}_x\text{CoO}_2$  positive electrodes, MCMB (Meso Carbon Micro Beads) negative electrodes, a liquid organic electrolyte, and a thermal shutdown separator. The electrochemical surface area of each cell is approximately  $750 \text{ cm}^2$ . Packaging is a Shield Pack class PPD laminate. Copper and aluminum current collection tabs are ultrasonically welded to the electrode stack tabs and brought out from the electrode stack through the heat-sealed seam of the package. See Figure 1.

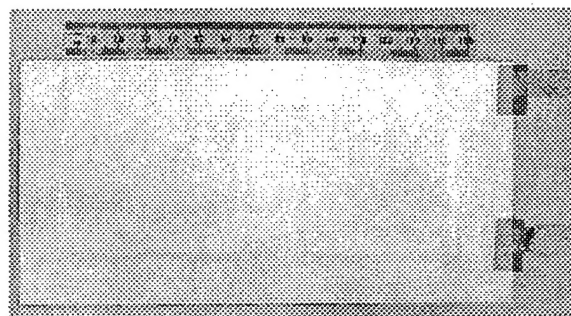


Figure 1: MSA 1.5 Ah Li-Ion Pouch Cell

Activation of the cells was comprised of an evacuation step to less than 100 microns vacuum followed by an electrolyte fill step in a closed system to minimize atmosphere ingress. Following activation, cells were subjected to a conditioning procedure, which included an initial low rate charge and one-week open circuit storage for aging. Then, cells were given ten C/5 cycles. Polarization scans were performed to assess rate capabilities of cells, after which the cells were discharged to 3.700 volts in preparation for battery assembly. Electrochemical impedance spectroscopy (EIS) and AC resistance (1000 Hz) measurements were also made and revealed no anomalies. The following attributes were chosen for the initial screening process. They are listed with the final data for 48 cells.

- Total Capacity Upon 10<sup>th</sup> Cycle Discharge {1706 – 1793 mAh, n = 48}
- Discharge Fade Rate Between 5<sup>th</sup> and 10<sup>th</sup> Cycle Discharges {2.5 – 3.8 mAh/cycle, n = 48}
- Load Voltage at 2.5C\* (~5mA/cm<sup>2</sup>) From Polarization Scans {3.733 – 3.797 Volts, n = 48}
- Self Discharge: Open Circuit Voltage After 3-Week Storage {3.744 – 3.765 Volts, n = 48}

\* C = current at the one hour rate; i.e., 1.5 amps per cell)

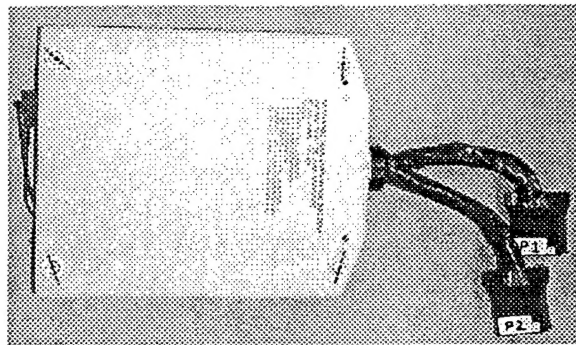
Selection of cells was made by eliminating outliers for each attribute of the 60 cells tested. Acceptable cells were then rank ordered by Total Capacity Upon 10<sup>th</sup> Cycle Discharge. Cells were distributed sequentially into eight groups, starting with the highest capacity cell going into the first group and ending with the lowest capacity cell going into the eighth group. This method of parallel pack matching results in the least difference in capacities within each six-cell group.

### **Battery Design**

Cells in the MSA battery are wired in a 6P x 8S configuration; i.e., six cells in parallel and eight such parallel strings in series. This configuration provides a nominal working voltage of 28.8 volts and a nominal capacity of 9 ampere-hours. Taps are provided for 28.8 volts and 14.4 volts.

Cell interconnections are made by stacking six cells in parallel, then ultrasonically welding the like tabs together. Each group of copper and aluminum tabs is ultrasonically welded to a nickel tab that had previously been soldered to a 10-gauge wire. Welded connections are taped and potted to provide strain relief.

Eight six-cell parallel packs are stacked two abreast and four high. The packs are secured with tape to prevent shifting. Two aluminum constraint plates, each 3 millimeters thick, sandwich the 48 cells to create a line-to-line fit within the battery enclosure. See Figure 2.



**Figure 2: MSA 9 Ah Li-Ion Battery (9" x 8" x 2.5")**

A thermocouple is located in the center of the battery for temperature data collection. Non-reversible temperature indicating labels are located throughout the battery.

### **Battery Testing**

The project did not include tasks for incorporating cell or battery level charge control or protective circuitry. In addition, the on-board nickel-cadmium battery charger and the lithium-ion battery were incompatible. Therefore, the eight six-cell packs have to be charged independently, not in series, and only series discharges are permitted. Consequently, series connections had to be made externally. The result is a 30 cm long battery wiring harness comprised of sixteen 10-gauge wires, two from each of the eight six-cell packs. Separate mating cables are provided for charge and discharge. The charge cable has sixteen 10-gauge wires and sixteen 18-gauge wires for separate six-cell pack cycling and voltage sensing, respectively. The discharge cable has hardwired series jumpers on its connector and three 10-gauge wires for the two voltage outputs. The large gauge wire is required to minimize voltage drop and maximize rate capability. See Figure 7.

Once connections were complete, the six-cell packs were constrained as described above, then tested as follows.

- **Step 1:** Charge to 4.100 V at C/5 (1.8A max) with taper down to C/50 (180mA)
- **Step 2:** Cycle (5) times at C/5 rate, 100% DoD, 3.000 volt cutoff, see Figure 3

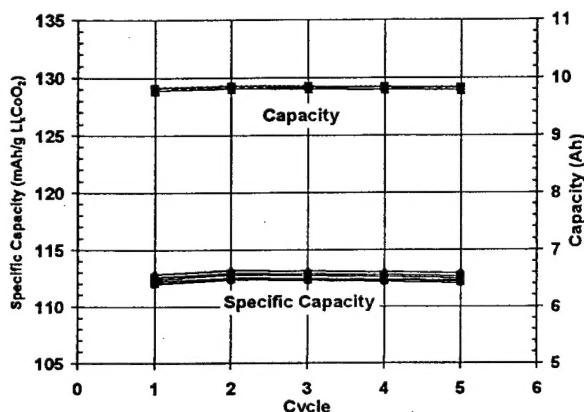


Figure 3: Specific Capacity and Capacity for Six-Cell Packs, n=8

- **Step 3:** Polarization scans -- 10 sec ON / 3 min OFF; 0.1 to 4.3 mA/cm<sup>2</sup>, see Figure 4

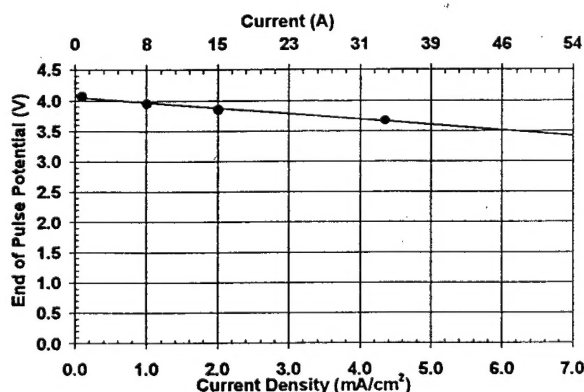


Figure 4: Polarization of Median Six-Cell Pack

The results from six-cell pack testing indicated all cells were performing as expected and were deemed acceptable. The headspace in the battery enclosure was potted with polyurethane foam sealing compound to protect the internal wiring and cell-pack connections. The battery was tested by charging individual six-cell packs, then discharging the six-cell packs in series. Individual six-cell packs were charged to 4.100 V at C/5 (1.8 A max) with a taper down to C/50 (180 mA). The battery was then discharged at

8, 12 and 16 amps to 24 volts (average 3.000 V/cell). The results from the discharge tests are very encouraging and are presented below.

## Results and Discussion

When discharged at the noted currents to a cutoff voltage of 24 volts, run times and capacities for the lithium-ion battery were obtained and are presented in Figure 5 and Table 1. The nickel-cadmium battery specification is listed for comparison and has a cutoff voltage of 22 volts. The internal temperature of the MSA battery was monitored. See Figure 6. Maximum temperatures of 40 °C, 45 °C and 50 °C were measured at 8, 12 and 16 amp constant-current discharges, respectively. This may explain the increase in capacity with an increase in load current.

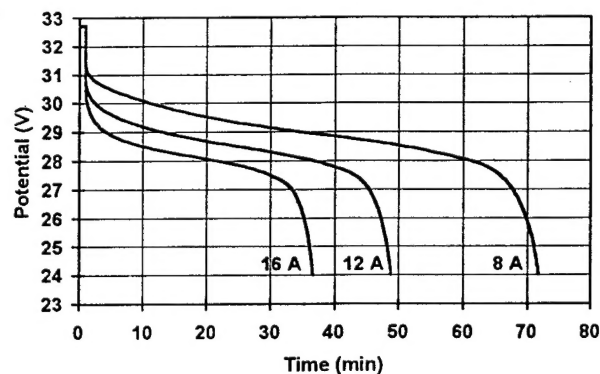


Figure 5: Performance Data for MSA 9 Ah Lithium-Ion Battery

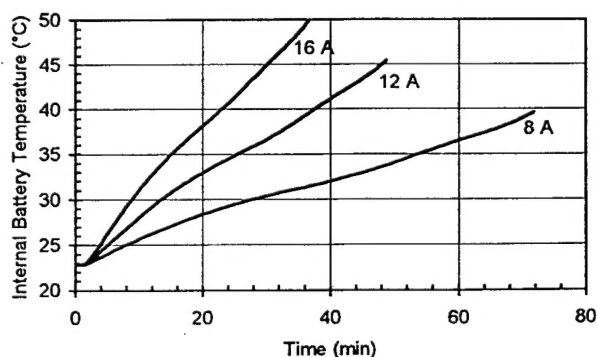


Figure 6: Temperature During Discharge for MSA 9 Ah Lithium-Ion Battery

## Conclusions

Although not optimized, MSA's lithium-ion battery provides a capacity increase of approximately 80 percent concurrent with a weight savings of 12

percent when compared to the nickel-cadmium battery. Capacity increase provides the benefit of extended aircraft recovery time and the weight savings can be converted into additional payload or fuel.

Further improvements in specific energy are expected when cell wiring connections and charge/discharge protective circuitry are incorporated inside the battery. This task was outside the scope of this project but should be addressed in future efforts. Wiring and circuitry

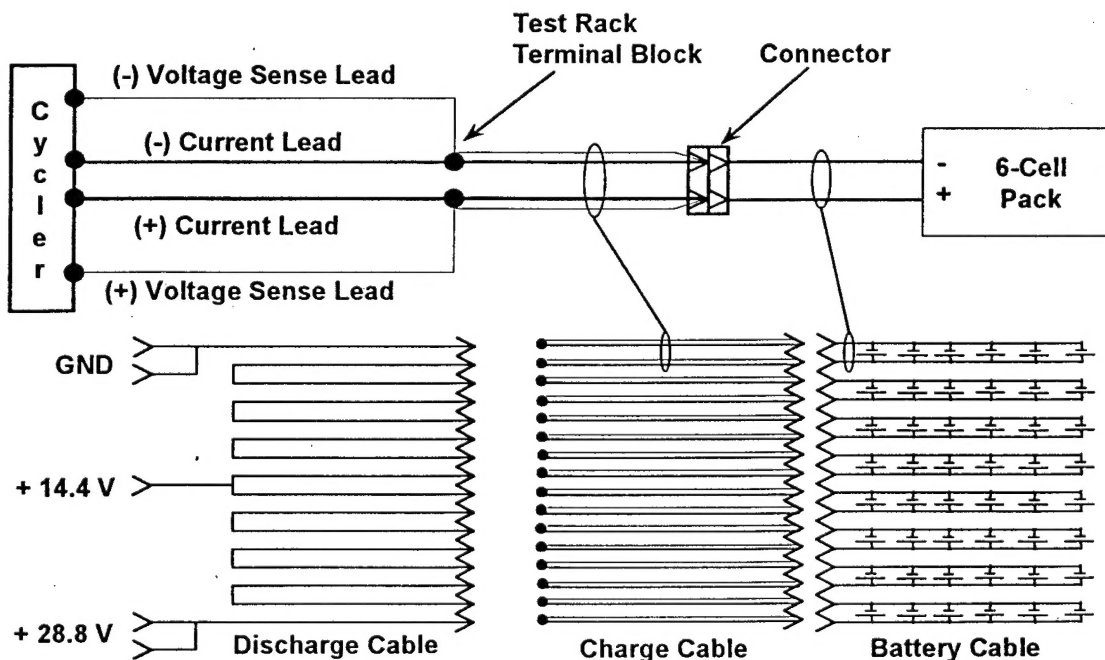
changes are estimated to increase the weight savings to approximately 20 percent, thus increasing the specific energy to more than 80 Wh/kg.

A lithium-ion battery developed specifically for this application would offer a variety of combinations of range, weight, and size. Once bench testing of the MSA lithium-ion battery generates sufficient data and warrants confidence in its performance, it is hoped that there will be an opportunity to fly the battery in the Pioneer or similar aircraft.

**Table 1: Performance Data for the MSA 9 Ah Lithium-Ion Battery vs. a Nickel-Cadmium Battery**

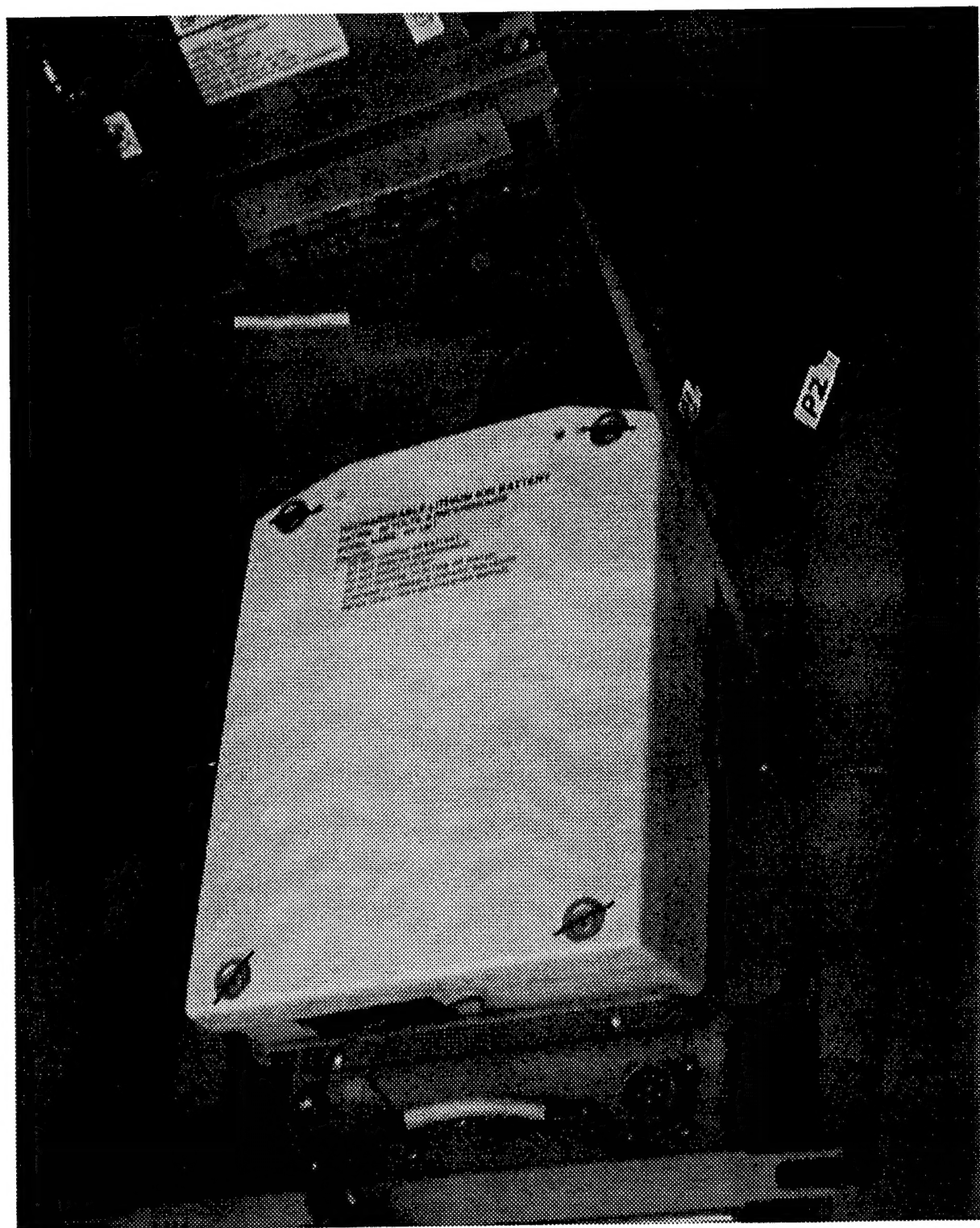
Battery Chemistry	Load Current (A)	Run Time (minutes)	Delivered Capacity (Ah)	Nominal Capacity (Ah)	Battery Weight (g)	Energy Density (Wh/L)	Specific Energy (Wh/kg)
Nickel-Cadmium	8	34	4.5*	5	4290	44*	30*
MSA Lithium-Ion	8	72	9.44	9	3780	92	73
MSA Lithium-Ion	12	49	9.56	9	3780	94	75
MSA Lithium-Ion	16	37	9.51	9	3780	95	75

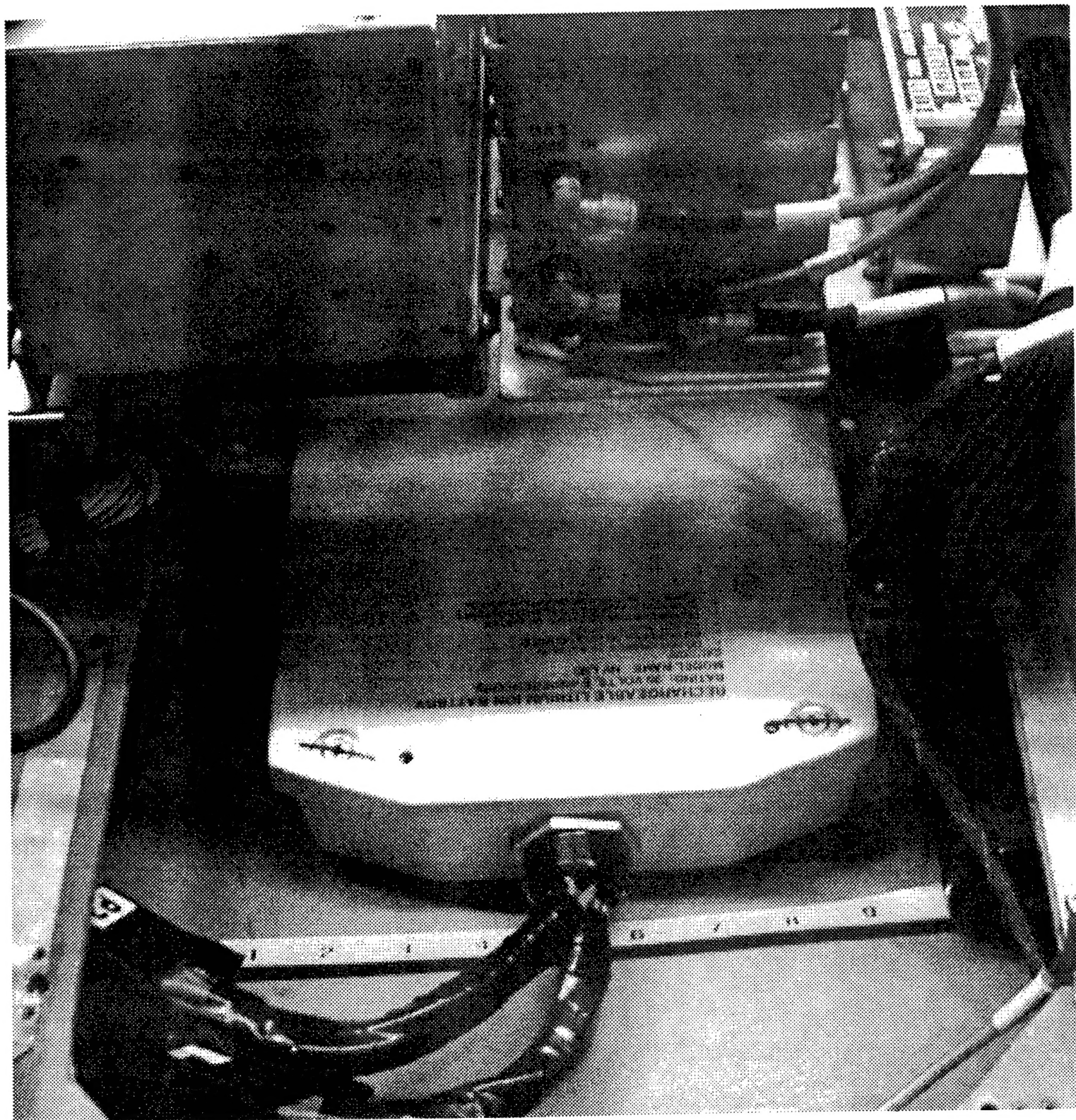
\* Calculated value using specifications for load current and minimum run time



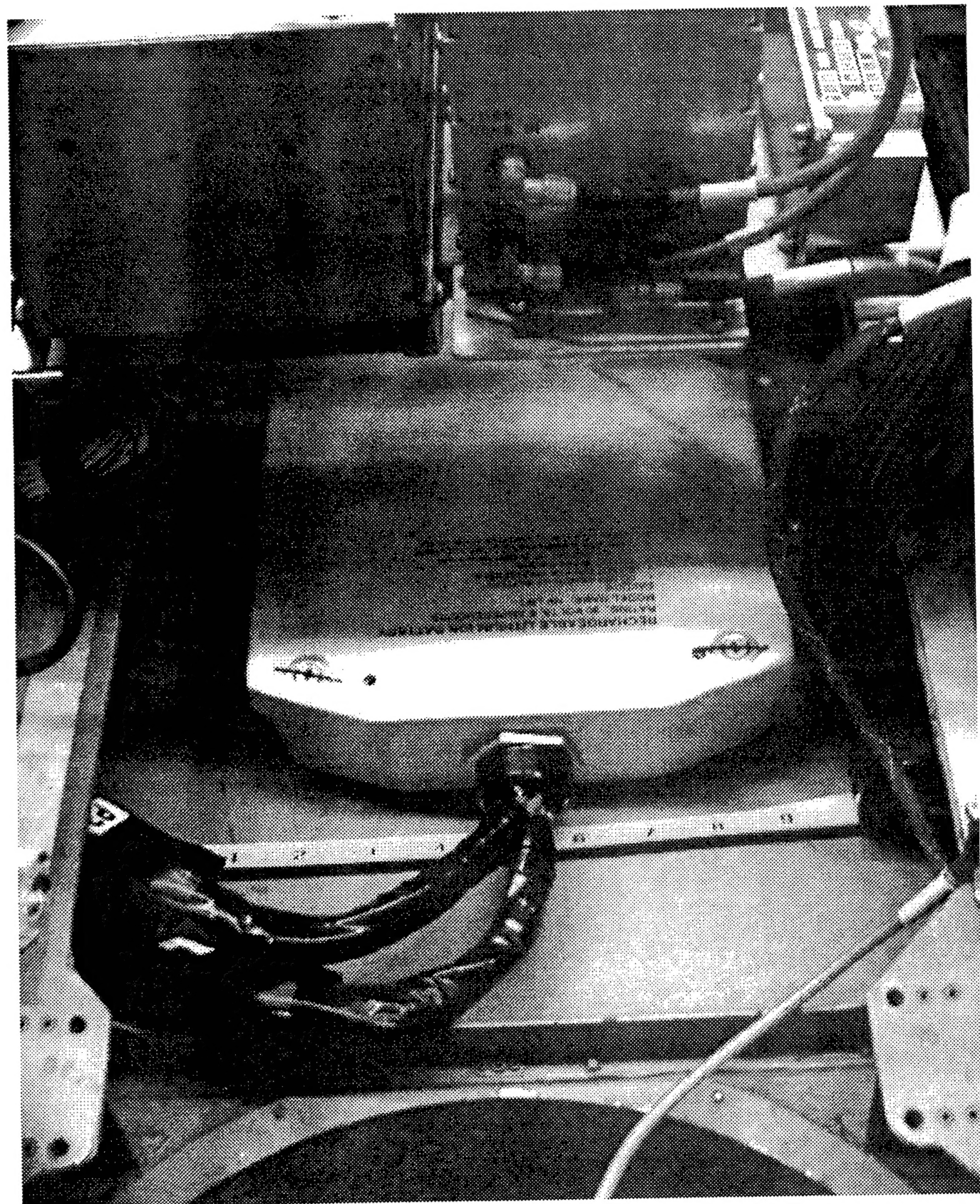
**Figure 7: Wiring Schematic For Charging of Six-Cell Packs and Discharge of Battery**







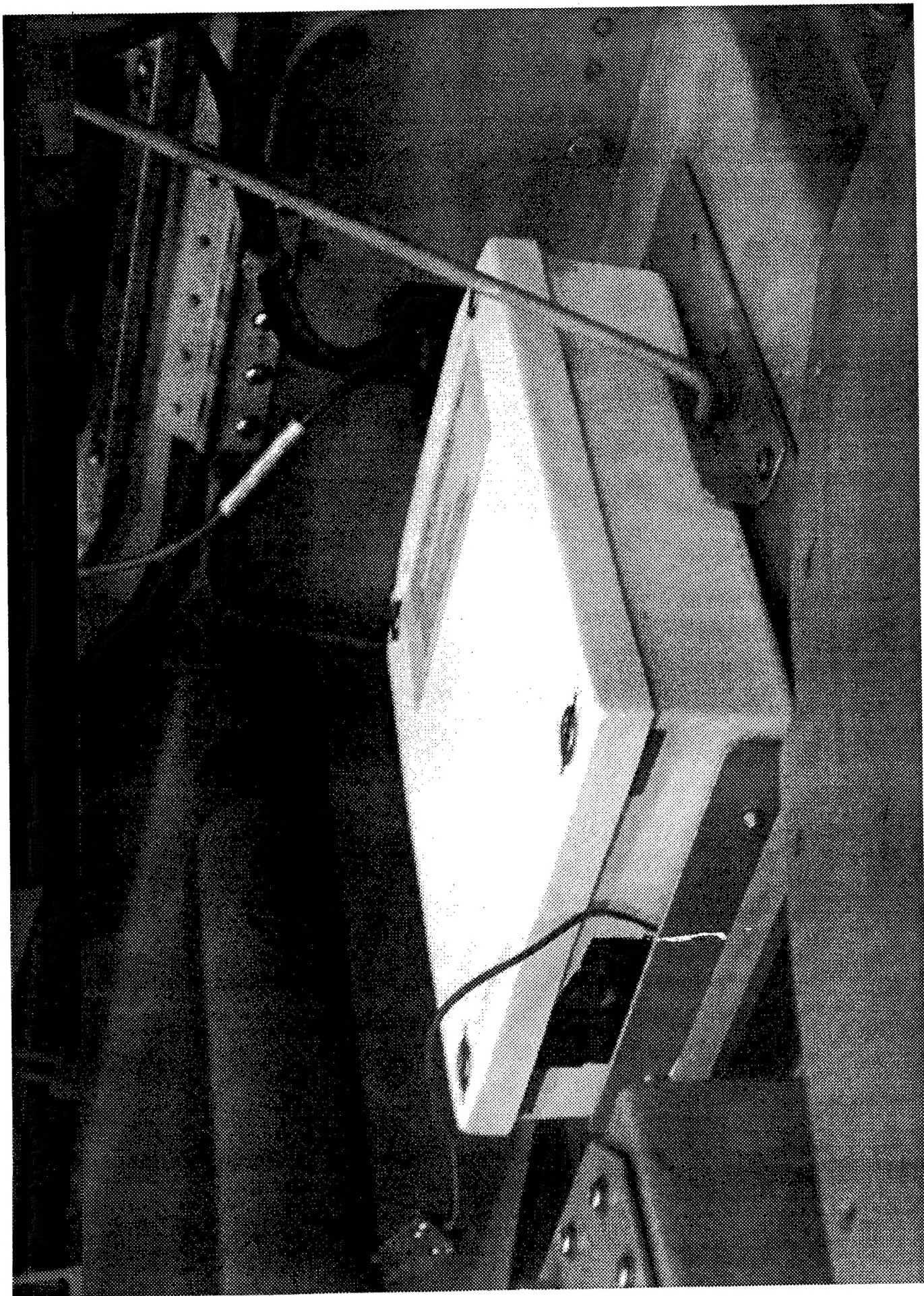




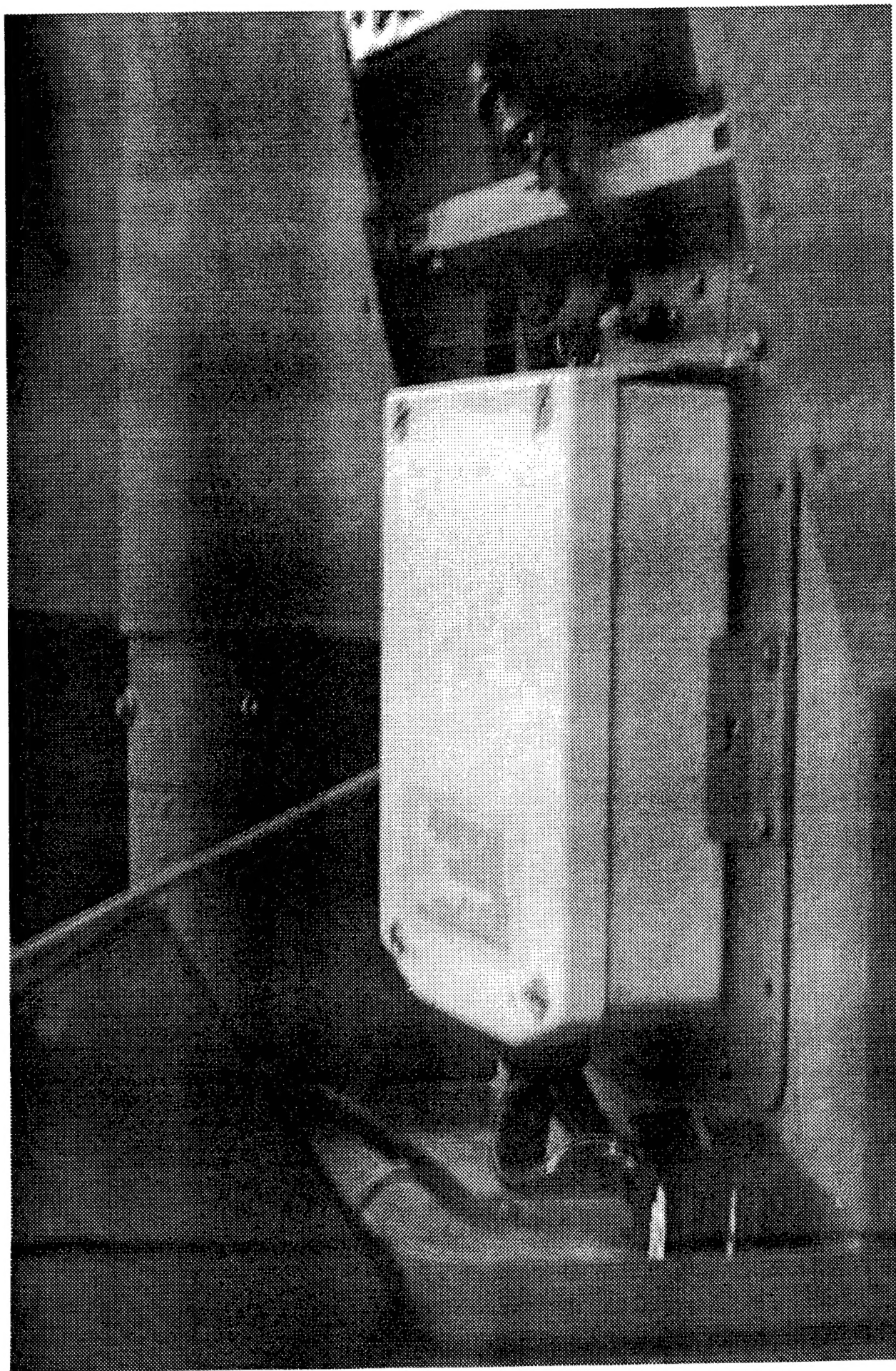
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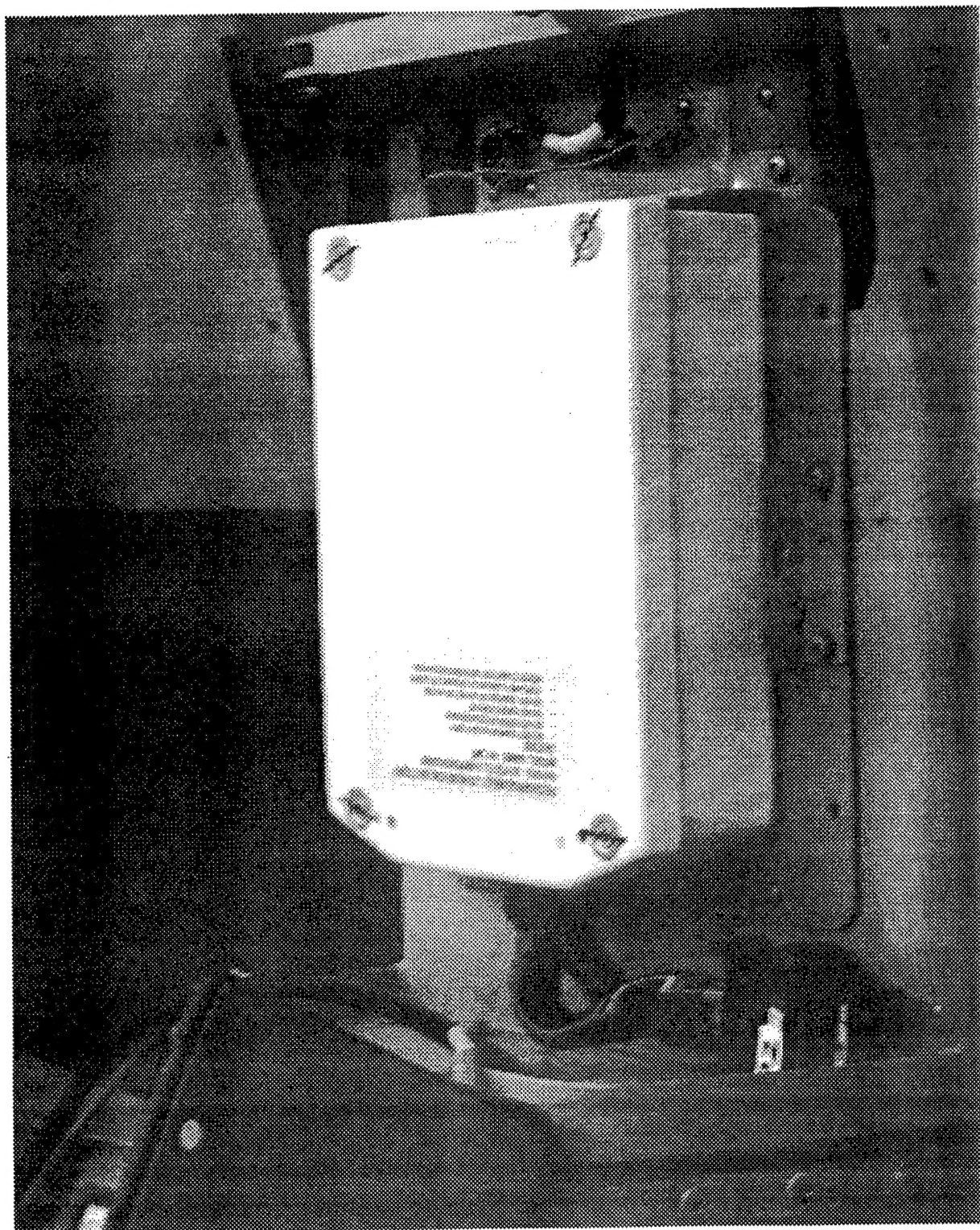
RECHARGEABLE LITHIUM ION BATTERY  
CAPACITY: 3000 mAh  
MODEL: 3000mAh 3.7V  
CHARGE: 100%  
- DO NOT DISCHARGE TO 0%  
- DO NOT OVERCHARGE  
- DO NOT SHORT CIRCUIT  
- DO NOT EXPOSE TO HIGH TEMPERATURE  
- DO NOT EXPOSE TO FLAME  
- DO NOT EXPOSE TO MOISTURE  
- DO NOT EXPOSE TO SOLAR RADIATION  
- DO NOT EXPOSE TO VIBRATION  
- DO NOT EXPOSE TO SHOCK



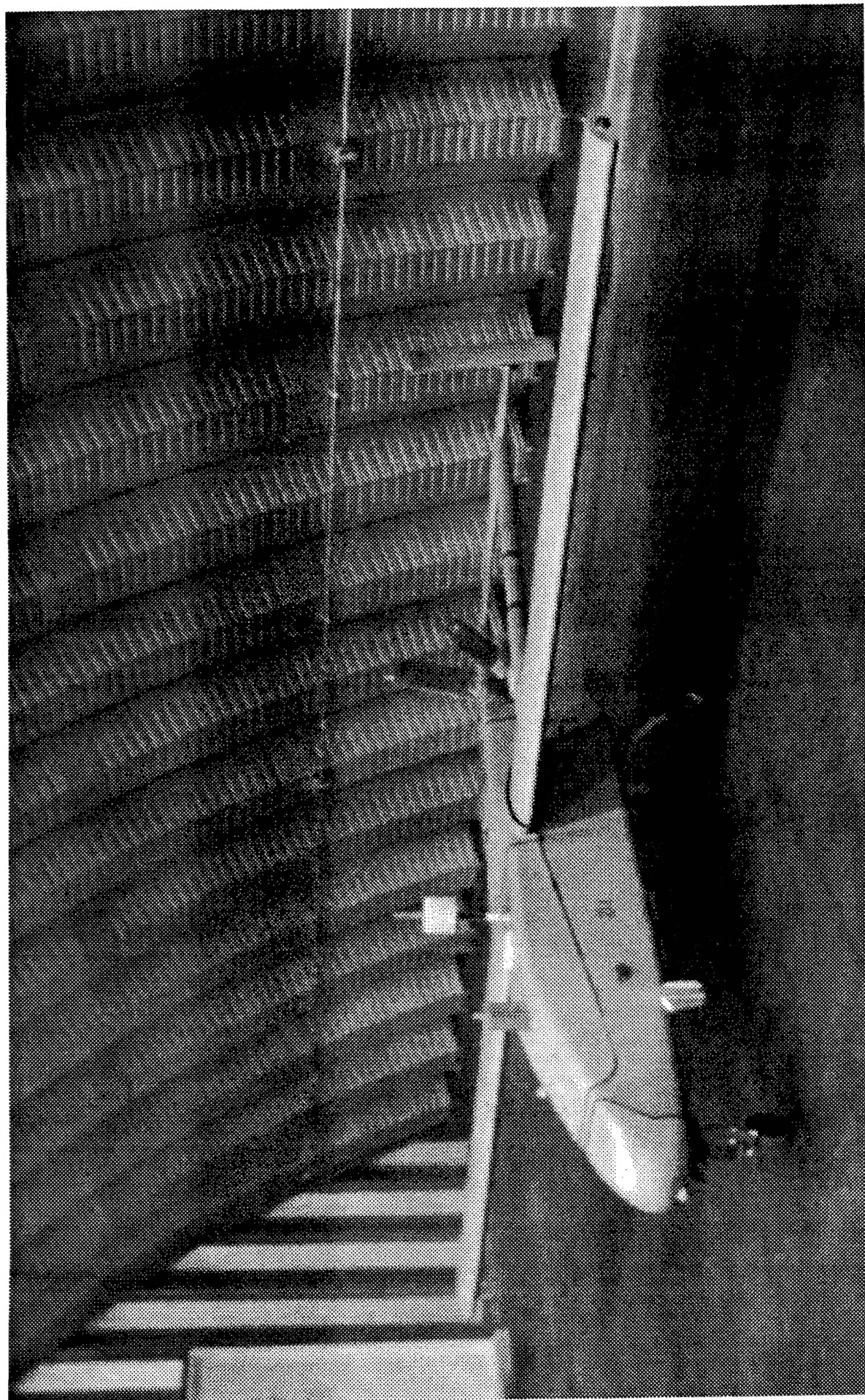












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